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Bolch, Tobias ; Gorbunov, Aldar P

Abstract: Northern Tien Shan is characterised by a distinct periglacial belt that contains many rock glaciers with an area of 1km² or more. To investigate the reason for their large size and variable occurrence, we analysed a representative subsample of the rock glaciers with respect to topographic and climatic variables. A simple permafrost model indicates that the rock glaciers originate in the zone where permafrost occurrence is very likely and some large rock glaciers flow down to elevations where permafrost is unlikely to exist outside the rock glaciers themselves. Correlation and multiple regression analyses revealed that the occurrence and characteristics of the rock glaciers can only be partly explained by the characteristics of the contributing area (e.g. its area or the headwall height). The correlation is greater with talus-type rock glaciers than with moraine-type rock glaciers. The climate can explain the general occurrence of rock glaciers but not their specific characteristics. It is hypothesised that the main reason for the specific distribution and characteristics of these large rock glaciers relates to the interaction with polythermal glaciers, topographic characteristics, intensive weathering and rock avalanches triggered by seismic activity.

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Characteristics and origin of rock glaciers in the northern Tien Shan (Kazakhstan/ Kyrgyzstan)

Tobias Bolch (1, 2) and Aldar P. Gorbunov (3)

(1) Institut für Geographie, Universität Zürich, Winterthurer Strasse 190, 8059 Zürich, Switzerland

(2) Institut für Kartographie, Technische Universität Dresden, 01062 Dresden, Germany, email: tobias.bolch@geo.uzh.ch

(3) Kazakstan Alpine Geocryological Laboratory, Permafrost Institute, Siberian Branch, Russian Academy of Sciences, P.O. Box 138, 050000 Almaty, Kazakhstan, e-mail: permafrost.08@mail.ru

Abstract

The northern Tien Shan is characterized by a distinct periglacial belt with the occurrence of many large rock glaciers. These rock glaciers are well described in the literature of the 1980s and the beginning of the 1990s. However, the reason for their enormous size and their variability of occurrence was not understood. Therefor we analysed a representative subsample of the rock glaciers with respect to topographic and climatic variables. We also included a simple permafrost model and could show that the rock glaciers originate in the zone where permafrost is very likely and some large rock glaciers flow down in likely permafrost-free area. Correlation and multiple regression analysis revealed that the occurrence and characteristics of the rock glaciers can only partly be explained by the characteristics of the contributing area, e.g. its area or the headwall height. The correlation is greater when examined with debris rock glaciers than with moraine-type rock glaciers. No significant relation of the lithology to rock glacier size could be found. The overall climate can explain the general occurrence but not its different characteristics. It is hypothesized that the main

reason for the specific distribution and characteristics of these large rock glaciers is related to the interaction with polythermal glaciers, intensive weathering and rock avalanches triggered by seismic activities.

Keywords: Tien Shan, Central Asia, Rock glacier, Permafrost, Morphometric Analysis

1. Introduction

Rock glaciers play an important role not only in the debris transport system in periglacial alpine environments, but also in the hydrological cycle (Humlum, 2000; Brenning 2005a; Azocar and Brenning, 2010). The latter is especially true for mountains with arid and semiarid climates, such as the Tien Shan in Central Asia (Bolch and Marchenko 2009). Destabilizing rock glaciers can also be a source of hazardous mass movements if they are situated on or move onto steep slopes (Roer *et al.,* 2008; Delaloye *et al.,* 2013). Typical origins of rock glacier debris include debris-laden snow avalanches (Humlum *et al.,* 2007), rock avalanches and rockfall activity (Johnson, 1984). Such processes can be triggered by weathering processes, debuttressing due to glacier recession, heavy rains or earthquakes (Haeberli *et al.,* 2006). Rock glaciers can also develop from moraines (Owen and England 1998, Vere and Metthews 1985). Rock glaciers mainly occur in the permafrost zone with favourable temperature conditions. Remains of glacier ice may also be embedded in rock glaciers (Haeberli and Vonder Mühll, 1996; Whalley and Martin, 1992; Berthling 2011).

Many rock glaciers are complex landforms and gradual transitions to debris-covered glaciers, portalus ramparts and moraines can exist under permafrost conditions (Haeberli and Vonder Mühll, 1996; Berthling 2011; Whalley and Martin, 1992). Rock glaciers can be classified according to the origin of the debris in talus-type rock glaciers and moraine-type rock glaciers (Barsch, 1996). Besides climate, rock glacier dynamics depend especially on the topography (Springman *et al.*, 2012; Delaloye *et al.*, 2013).

Several studies show that there is a relationship between the rock glacier size and contributing area parameters, such as rockwall extent or the size of the contributing area (Bolch and Schröder, 2001; Frauenfelder *et al.*, 2003; Brenning and Trombotto, 2006, Janke and Frauenfelder, 2008), and altitude, aspect, and potential insulation (Olyphant, 1983).

Rock glaciers are common features in the northern Tien Shan and first descriptions date back to the first half of the 20th century, starting with a measurement of a rock glacier front in 1923 (Palgov, 1932; Goloskokov, 1949, Iveronova, 1950). A possible permafrost origin for rock glaciers was proposed in the mid-1950s accompanied by more detailed investigations on permafrost (Gorbunov, 1967). The rock glaciers were then studied and described in more detail in the 1970s and 1980s (Gorbunov and Titkov, 1989). It was then believed that these rock glaciers are mainly of periglacial origin but can also contain sedimentary ice (Gorbunov, 1979; Gorbunov and Titkov, 1989). Gorbunov (1983) concludes that the occurrence and density of the rock glaciers in northern Tien Shan depends - besides climate - on factors such as the shape and size of the contributing area, maximum and average wall height, lithology, and avalanche processes. However, these estimates are vague and the reason for their occurrence and their distribution in the northern Tien Shan and in other mountains of the world is still not fully understood. E.g. to date it is still unknown, for example, how large rock glaciers can evolve from small contributing areas, or why rock glaciers exist in one valley, but not in the neighbouring one. Despite their importance only few recent studies about the rock glaciers in northern Tien Shan were published in the international literature (e.g. Schröder *et al.,* 2005).

The purpose of this study is therefore (i) to quantify the potential topographic controls on the rock glacier occurrence using GIS and morphometric analysis and (ii) to discuss the previous studies and the derived new results in the context of the current scientific knowledge and in a global context.

2. Study area

2.1 General Characteristics

The mountain ranges Ile Alatau (former name: Zailijskij or Transili Alatau) and Kungöj Ala-Too (Kungej Alatau, 42°30' to 43°30' N, 75° to 79° E) of the northern Tien Shan are located at the border between the Central Asian countries Kazakhstan and Kyrgyzstan (Fig. 1). These ranges rise from the Kazakh Steppe at an elevation of about 800 m asl. to nearly 5000 m asl. The southern edge is an intra-mountainous basin with Isyk-Köl Lake (also: Issyk-Kul, 1608 m asl).

Figure 1 around here.

The mountains of the northern Tien Shan originated from the Caledonian orogenesis but are still affected by compression and are slightly uplifting. The area is situated within the Chilik-Kemin seismic zone (Chedija, 1986). Several predominantly WSW-ENE-striking faults occur. The Ile and Kungöj Alatau are separated by floored depressions filled by Quaternary sediments and incised valleys such as Chon-Kemin Valley. The mountains are formed mainly of granites of Devonian, Silurian, and Carboniferous age. Cambrian gneisses occur in the Kungöj Ala-Too. The lower slopes and incised valleys occur in more easily eroded Cambro-Ordovician schist. The mountain ranges are mainly formed by neo-tectonic activity (Chedija, 1986). Several major earthquakes have occurred and thousands of smaller seismic events have been recorded since the end of the 19th century (Lukk *et al.*, 1995; Yadav and Kulieshhius, 1992; Delevaux *et al.*, 2001).

Due to the topography, the overall continental climate is characterized by distinct local variability. At altitudes about 3000 m asl, precipitation ranges from more than 1000 mm/a on windward northern slopes to less than 800 mm/a in a leeward valley south of the main mountain ridges. Precipitation minima occur in all areas in winter due to the Siberian anticyclone and the maxima in early summer due to cyclonic activity and convective precipitation (Bolch, 2008). Mean annual air temperature (MAAT) at Tuyuksu glacier station (3434 m asl) varies around -4 °C. The zero degree isotherm line is situated just above 2700 m asl. The temperature increased significantly (~1 K) since the 1950s both in the lowlands and in the mountainous area above 3000 m (Aizen *et al.*, 1997; Bolch 2007). The steady-state equilibrium line altitude of the glaciers is situated about 3800 m asl on northern slopes and between 3900 and 4000 m asl on southern slopes while the termini of the glaciers can reach down to 3400 m asl (Bolch, 2007). Temperatures at 15 m depth on the middle parts of the tongue of Tuyuksu Glacier were measured to be -1.7 to -1.8 °C all year round while measurements in the firn zone at 10 m depth revealed higher temperatures of -0.3 °C (Makarevich, 1985). Hence, the glaciers in the study area are most probably polythermal and permafrost is very likely in the surroundings even for the lowermost parts of the glacier tongues.

2.2 Permafrost and rock glaciers

A characteristic feature of the northern Tien Shan is its pronounced periglacial zone which is characterized by frequent diurnal freeze-thaw cycles (Marchenko, 2003a; Marchenko *et al.*, 2007). Permafrost is sporadic (less than 30% of the area is continuously frozen) at about 2700 – 3200 m asl, discontinuous (less than 70% is frozen) at 3200 – 3500 m asl, and continuous (more than 90% is frozen) above 3500 m asl (Gorbunov *et al.*, 1996). The thickness of the permafrost varies between 10 and 80 m (Marchenko, 2003b). Geothermal observations indicate warming of the permafrost by 0.3 – 0.6 K from 1974 to 2004 while the lower boundary of permafrost has shifted upward about 150-200m since the beginning of the

20th century and the area of permafrost decreased by approximately 18% (Marchenko *et al.*, 2007).

Many large, active rock glaciers occur in Ile and Kungöj Alatau (Figure 2). These rock glaciers are among the best described in the Central Asian mountains. Based on aerial photography, 429 active and 75 inactive rock glaciers in Ile, and 422 active and 108 inactive rock glaciers in Kungöj Alatau (which cover a total area of 90.3 km^2) were identified (Gorbunov *et al.*, 1998). Active rock glaciers were classified into two main types, moraine-type (321 in total) and talus-type (530 in total). Whereas the latter prevail in number, the former cover a larger area (54.8 to 35.5 km^2 respectively; Gorbunov and Titkov, 1989). The majority of the rock glaciers are located in the elevation range of 3000 to 3800 m asl while the average elevation is ~3400 m asl (Gorbunov and Titkov, 1989). The lowest elevation of an active rock glacier front is about 2500 m asl (Gorbunov, 1983) which is even below the treeline. There are also some fossil rock glaciers. One of them, situated in the Esik (Issyk) basin, terminates as low as 2200 m asl (Gorbunov and Titkov, 1989). In this basin the largest complex of seven aggregated rock glaciers, probably of different ages, exist and can be distinguished from two relict rock glaciers. The longest is about 2.9 km in length. Several rock glaciers are larger than 1 km^2 and the largest covers more than 2 km^2. Some of the most impressive rock glaciers, and the ones that have been most intensively studied, are the active moraine-type rock glaciers Gorodetzkij and Morrenij in Kishi Alamty (Bolshaja Almatinka) valley. These rock glaciers have an average slope of 15-20° with a 40-45° steep front. They are up to 1.3 km long, up to 1 km wide, and have a thickness at the front of 20-50 m (Glazovskiy, 1978; Gorbunov and Titkov, 1989).

Figure 2 around here.

Surface velocities for several rock glaciers in the northern Tien Shan were measured based on displacements of larger boulders using ground surveys and aerial imagery. Annual velocity ranges from less than 1m to about 11 m (Gorbunov and Titkov, 1989; Gorbunov *et al.*, 1992). Multi-temporal terrestrial measurements on the fronts of some rock glaciers in northern Tien Shan allow the calculation of its advance. The longest record, dating back to 1923, is from the Gorodetzkij rock glacier in Ulken Almaty valley is showing an advance of 0.8-0.9m/a from 1923-1977 to about 1.6 m/a since the mid 1980s until ~2000 in the centre part (Bolch and Marchenko, 2009). Also the average surface displacements of the measured boulders increased from the period 1969 – 1979 to the period 1979 – 1994, except in the case of the Karakorum rock glacier (Gorbunov and Titkov, 1989, Gorbunov *et al.*, 1992). Displacement rates of the rocks differ greatly within individual rock glaciers and areas of inactivity exist (Gorbunov and Titkov, 1989; Gorbunov *et al.*, 1992). The average surface velocity rates of the rock glaciers in northern Tien Shan are higher in comparison tothe majority of the rock glaciers in the Alps (Kääb *et al.*, 1997; Roer *et al.*, 2005) or the Rocky Mountains (Janke, 2005) where the rates are usually some decimetre per year. However, there are also some fast moving rock glaciers documented in the Alps situated on steep slopes and were destabilizing (Roer *et al.* 2008, Delaloye *et al.*, 2013).

3. Investigations based on remote sensing and GIS

Rock glaciers in six selected valleys were manually mapped based on an orthorectified Landsat ETM+ scene acquired on August 8, 1999 using ArcGIS. Two ASTER scenes from 2000 and 2001, as well as GoogleEarth™ and aerial photographs taken in 1990 (~1 m resolution) provided additional information. The glacier-cover is based on the 1999 Landsat scene (Bolch, 2007). The investigated valleys are selected based on the availability of information from existing literature, the accessibility for ground truth, and should represent different climatic conditions, such as the more humid northern slopes of Ile and the more arid Kungöj Alatau. Rock glaciers included in the analysis are those that could clearly be identified as active. Possible rock fall deposits without signs of creep and debris-covered glaciers were excluded. The investigated valleys were visited and the front position of the larger rock glacier measured using GPS.

Figure 3 around here

The contributing area of each rock glacier was calculated using the hydrological analysis tool of ArcGIS based on the void filled version of the SRTM3 digital terrain model (DTM) with 90m resolution from CGIAR (http://srtm.csi.cgiar.org/). All contributing areas were visually checked and if necessary manually improved based on the flow direction grid and the remote sensing data. The SRTM3 DTM was also utilized to calculate the slope gradients and the aspect. The mean annual precipitation and the mean annual air temperature (MAAT) were regionalized based on a regression model using the DTM, the mean annual values of 21 climate stations and statistical downscaling of reanalyzed precipitation data (Bolch, 2008).

The permafrost distribution was modelled in order to get the information about the possible glacier-rockglacier-permafrost interaction. We selected the widely used model Permakart (Keller 1992), which is based on empirical findings and topographic parameters only, as no detailed measurements for the larger study area were available. We extended this model and included the solar radiation as it is an important factor for the permafrost distribution (Funk and Hoelzle 1992). The solar radiation was modeled using the “Sunray” program, taking the standard astronomic and atmospheric parameters, such as the geographic position or the atmospheric extinction, and topographic effects into account (Bolch, 2008). Additional boundary conditions for the model were provided by the regionalisation of the MAAT and the limits of the permafrost distribution (Gorbunov et al., 1996, see also above). The physical model by Marchenko (2001) developed for a small subset of the study area (Kishi and Ulken Almaty Valley) served as an evaluation dataset. Overall, the model showed a good agreement with the modelled and measured results, but small-scale variability (e.g. caused by the landcover) could not be captured. For each rock glacier (RG) and its contributing area (CA), the following parameters were calculated using ArcGIS (Table 1):

Table 1 around here

The headwall area was estimated to be the steeper slopes above 30° within the contribution area. We choose a slightly lower slope threshold than Zemp *et al.* (2005) who suggested 34° because we used a coarser resolution DTM. The height was calculated from the maximum elevation of the contributing area and the maximum elevation of the rock glacier ($h_{HW} = hCA_{max} - hRG_{max}$). The area was calculated based on the projected 2d area and the mean slope. In addition the following ratios were calculated: area/perimeter ($R_{a/p}$), area/elevation range ($R_{a/hrange}$), and area/slope ($R_{a/sl}$). The lithology of each rock glacier was identified from geological maps (scale 1:200,000) (USSR, 1974) and field investigation. The variables were then investigated for their correlation to the rock glacier size (a_{RG}) and the lowermost elevation of the rock glaciers (h_{minRG}) and by multiple regression analysis. In addition, a significance test based on the 95%-confidence level was carried out. Areas and lengths may differ slightly from those presented by Gorbunov and Titkov (1989) and Gorbunov *et al.* (1992). This is mainly due to the difficulty of determining the moraine type rock glacier heads and because the rock glaciers changed over the observation times.

4. Results and Discussion

4.1 Rock glacier identification and inventories

We identified 72 rock glaciers (Figure 3). Sixty of them are of the moraine-type. Several of the talus-type rock glaciers mentioned by Gorbunov and Titkov (1989) could not be identified clearly using the remote sensing data, and were therefore not included in the analysis. The smaller portion (12 of the 72) compared to the previous results (Section 3) can be explained by the small area size of this rock glacier type making them more difficult to identify and to distinguish between rock fall or landslide deposits. Several of the features that have been identified as rock glaciers in the northern Tien Shan originate from lateral moraines or slope deposits. Maps showing rock glaciers in Tien Shan are rare and show mainly the larger moraine-type rock glaciers (e.g. the map of Glazovskiy [1978] of the rock glaciers in Ulken Almaty (Bolshaja Almatinka) valley shows eight morainic rock glaciers, one talus rock glacier, and three relict rock glaciers, but the inventory [Gorbunov *et al.*, 1998] indicates that there are twelve morainic, four talus and eight inactive rock glaciers). Using aerial images we could clearly identify only eight active rock glaciers in this valley. It is possible that embryonic rock glaciers were included in the existing inventory. A detailed map of the rock glaciers in the central mountain knot of northern Tien Shan (including Talgar, Chon-Aksu and Chon-Kemin valleys), published by Schröder (1992) also differs from our identified rock glaciers. These differences stem probably from the use of different definitions of features and the difficulties in identification and in separating relict, inactive, active rock glaciers from similar looking features. Overall, about 80% of the rock glaciers of the previous inventory of the same valleys (Gorbunov and Titkov, 1989) could be included in this analysis. Our analysed subset can be seen as representative for the topographic and climatic variables, e.g. the altitudinal ranges are similar to those presented by earlier inventories. General statistics about the rock glaciers and their contributing areas in the studied valleys are shown in Table 2 while detailed characteristics of selected larger rock glaciers are presented in Table 3.

Table 2 around here

Table 3 around here

4.2 Rock glacier density and lithology

The rock glaciers in the investigated valleys cover about 3% of the area in the elevation range above 3000 m asl. The rock glacier area is about 15% of the area covered by glaciers (~ 600 km²). Gorbunov (1983) suggested to calculate the rock glacier density as the ratio of the total area of rock glaciers in a basin to the area above the lower limit of the rock glacier occurrence in this basin. The average density would then be ~1.5% with the lowermost rock glacier front terminating at 2500 m asl. The highest density of rock glaciers (>4%) can be found in the central and western part of Ile Alatau as well as in some north facing side valleys of the Chon-Kemin and Chilik valley where the percentage of glacierized terrain is 10-20% (Gorbunov, 1979; Titkov, 1988). The specific rock glacier density in the northern Tien Shan is therefore clearly higher than in the Swiss Alps and the Mt. Everest Region, Nepal, where Gorbunov (1983) calculated a density of 0.33% based on the data by Barsch (1977) and 0.15% based on Higuchi *et al.* (1978) respectively. However, even higher densities were presented for the Andes of Santiago (6.7 ± 1.3%) and the Andes of Mendoza (5.0 ± 1.5%, Brenning, 2005b).

The rock glacier density in northern Tien Shan is lower in less glacierized areas and higher in areas with larger ice cover. An exception is the area with highest glacierization around the central part of the mountains where Ile and Kungöj Alatau meet and the east facing Chilik valley has unfavourable conditions for rock glaciers because the glaciers cover large areas of the elevations where otherwise rock glaciers could develop (Gorbunov and Titkov, 1989; Titkov, 1988). In addition, the rock glacier density decreases towards the margins of the mountain ranges with decreasing elevations of the ridges where also the glacierization decreases. This fact allows the conclusion that the occurrence and characteristics of rock glaciers is to a high degree influenced by the polythermal glaciers and, hence, the availability of glacier meltwater.

The lithology of the investigated rock glaciers and their contributing areas are dominated by granite. Sixty of the 72 investigated rock glaciers are comprised of this slowly weathering rock type. The remaining rock glaciers consist of gabbro, andesite, porphyry and less resistant schist. However, no correlation was found between the rock type and the rock glacier size ($r < 0.1$). Bedrock lithology might have a minor influence on some rock glaciers, e.g. for the Karakorum rock glacier that is not dominated by granite. Several other studies have shown that bedrock has an influence on the size of the debris particles but not on the occurrence of the rock glaciers themselves. Granites and porphyritic volcanic rocks produce, in general, large boulders (Haeberli *et al.*, 2006; Matsuoka *et al.*, 2005) and most of the large rock glaciers in the world as well as in the Tien Shan consist of these bedrocks.

4.3 Topography (Relationship between rock glacier area and contributing area variables)

Our analysed subset reveals that a large amount of the rock glaciers are north-facing (43%). Twenty-five percent have southern aspects including the second largest rock glacier (1.62 km²) in the dataset. The largest rock glacier, which covers almost 2 km², flows to the northeast. Gorbunov and Titkov (1989) who showed that most rock glaciers in Ile Alatau are on north-facing slopes, whereas in Kungöj Alatau the dominant aspect is south-facing. We found no significant correlation between the aspect of the rock glacier and its contributing area and the rock glacier size. Northern aspects favour rock glacier occurrence; this is however (as for the radiation, see below) not significant. The dominance of the north facing rock glaciers in Ile Alatau and south-facing in Kungöj Alatau might be influenced by the topography with slightly dominant north facing slopes for the former range and south-facing for the latter. The largest rock glaciers in the Swiss Alps are located in western aspects (Frauenfelder *et al.*, 2003). In contrast, Sloan and Dyke (1998) attribute the aspect of high importance in the Selwyn Mountains, Yukon Territory/Canada, with the longest rock glaciers flowing to the north-east. Hence, there might be a favourite aspect for the rock glacier development, but it cannot be generalized for all mountain ranges of the world.

We found a slight correlation between rock glacier area (a_{rg}) and the ice-free contributing area (r=0.34, Table 4). The correlation can be seen as significant based on the 95%-confidence level but the relation is much weaker than with rock glaciers in other study areas, for example the Colorado Front Range (Janke and Frauenfelder, 2008). The rock glacier area (a_{rg}) is also slightly influenced by other relief parameters, such as the maximum elevation of the contributing area (r_{hmaxCA}=0.33), headwall height (r_{hHW}=0.33, Figure 5), maximum slope (r_{SLmax}=0.34), area/slope ratio (r=0.28), and the form of the contributing area, represented by the quotient of $a_{ca,}$ and the perimeter of the contributing area (r=0.52). A similar correlation of 0.52 also exists for the elevation range of the contributing area. A slight positive association exists also with the area of the headwalls, but with low significance. The correlation is stronger for the talus rock glaciers only, e.g., r_{hmaxCA}=0.62, r_{SLmax}=0.61. This can be expected as this rock glacier type is more directly connected to the bedrock topography. However, the number of investigated entities is small (12). The minimum elevation of the rock glaciers is slightly correlated with the relief parameters and the area of the contributing area. The highest negative correlations are with the area/perimeter ratio (r=-0.47), maximum slope (r=-0.47), and headwall height (r=-0.50). h_{min}RG also correlates negatively with its area (Table 4).

Table 4 around here

Figure 5 around here

A multiple regression analysis revealed that about 45% of the variability of the area of the rock glaciers can be explained by the topographic variables which had a significant relationship on the 95%-confidence level. Including all topographic variables would only increase R^2 only to slightly more than 50%. Both analyses were significant. Hence, the debris supply of a rock glacier is influenced by the contributing area characteristics. However, the correlations between rock glacier area and contributing area characteristics are weaker compared to a similar study in the Colorado Front Range (Janke and Frauenfelder, 2008). A reason might be the backweathering rates of the headwalls which significantly vary in different climate regimes (Müller *et al.*, 2014). However, no data is known for the study region. In case of the northern Tien Shan, there is also a tendency that larger contributing areas produce larger rock glaciers, but the r-value of 0.34 is less than that in the Colorado Front Range (Janke and Frauenfelder, 2008). The correlation coefficient of the rockwall height against the rock glacier area of the Colorado Front Range is comparable to that of the study area (r=0.29 to 0.28). The highest correlation exists between the form of the contributing area and the size of the rock glacier. The longer and narrower the contribution area, the more likely rock glaciers to be large (r=0.52). In contrast, Janke and Frauenfelder (2008) report the highest correlation between the width of the contributing area and the rock glacier size. Correlations between the minimum elevation of the Tien Shan rock glaciers and the contributing area are similar than the correlation with the rock glacier area. Only the maximum slope of the contribution area has a clearly higher correlation coefficient (r=-0.47, Table 4). Also, the results of the multiple regression analysis were similar. Hence, the rock glacier size and their minimum elevation can only be partly explained and the correlations between rock glacier area and contributing area characteristics and further important mechanisms and processes need to be important as well. The correlation between the talus-type rock glaciers and their contributing areas are in general higher than for the moraine type. Hence, the talus-type rock glaciers are more influenced by the overall topography as the system is not influenced by the glacier-transport.

4.4 Climate and Permafrost

Temperature and radiation are amongst the most important variables influencing permafrost distribution. Figure 6 presents the result of the permafrost model with the location of the rock glaciers. This indicates that the rooting zone of the rock glaciers is mostly situated in the zone with discontinuous permafrost and partly in the continuous permafrost zone. The smaller rock glaciers terminate either in the lower zone of discontinuous permafrost or in the upper zone of sporadic permafrost while the larger ones terminate partly even lower than the modeled lower bound of the sporadic permafrost. Hence, the lower reaches of the rock glaciers contain warm permafrost.

The potential direct solar radiation input on the rock glaciers is only slightly lower than that of their contributing area and within the range of the mean radiation values for the whole mountain range. Radiation of the contributing area correlates slightly with the minimum elevation of the rock glacier, but not with the rock glacier size. The highest correlation is between MAAT at the elevation of the rock glacier and its area (r=0.33). However, this variable is not independent, because the larger rock glaciers reach further down in the valleys to lower elevations and have therefore higher mean annual temperatures. The mean annual air temperature (MAAT) at the rock glacier sites is below freezing, but the fronts of the lowest rock glaciers (below 2700 m asl) are likely to be situated in areas with slightly positive

MAAT. There is a negative correlation between MAAT of the contributing area and lower limit of the rock glaciers (Table 4). The inclusion of T_{mean} CA and rad_{mean} CA in the multiple regression analysis increased the percentage of the variability to explain the rock glacier characteristics especially for the minimum elevation for more than 10%. Hence, the overall climate is important for the rock glacier occurrence and their characteristics in general. However, the specific distribution, size and lower limit can only be marginally explained by the climate and its differences.

Figure 6 around here

4.5 Other influences and rock glacier origin

The presented data show that many factors are important for the rock glacier occurrence, developments and characteristics. Contributing area and climatic parameters can only partly explain their size and distribution. Long-term growth of rock glaciers requires continuous debris input. Therefore high rock weathering rates in the contributing area should be expected. No measurements of sediment flux in the contributing area are available so far to our knowledge, but climate data and ground temperature measurements at Zhusalykezen Mountain pass (3330 m asl, situated between Ulken Almaty and Prochodnaja Valley; Marchenko, 2003b) shows that seasonal and daily freeze-thaw cycles are to be expected in the elevation range of the contributing areas. Furthermore, an investigation of ground surface temperatures in Prochodnaja Valley confirms freeze-thaw cycles at elevations over 4000 m asl. Areas affected by freeze-thaw weathering cover the ice-free rocky areas above 3500 m asl in this valley (Munack, 2006). Avalanches might also have an effect on rock glacier development as they are common in northern Tien Shan.

Nevertheless, none of the facts mentioned above can really explain how large rock glaciers develop from relatively small contributing areas (e.g., Morrenij rock glacier) or why there are rock glaciers in one valley, but few or none in adjacent valleys (e.g., Karakorum rock glacier). A possible reason could be the large contributions of rock avalanches triggered by earthquakes or other spatially discrete mass movements which has been suggested by Gorbunov (1983). Many of the large rock glaciers in Northern Tien Shan are situated close to major faults (Figure 3). Several studies have confirmed that landslides and rock avalanches in the Northern Tien Shan were triggered by earthquakes (Delevaux *et al.*, 2001; Havenith *et al.*, 2003). If the rock deposit occurs at a site favourable for the development of ground ice a rock glacier could develop. This could even be in areas with an MAAT above 0°C because thermal conditions in blocky material are favourable for permafrost. Measurements in the Ile Alatau Range during the period of 1974–1987 show that the temperatures inside the coarse debris are typically 2.5-4.0°C colder than MAAT (Gorbunov *et al.*, 2004). These depressed temperatures are also one reason that the rock glaciers extend a few hundreds meters below the glaciers in the northern Tien Shan, and also lower than the sporadic permafrost and why some larger rock glaciers reach forested areas. It is mentioned in the literature that rock deposits of some landslide deposits could be misinterpreted as rock glaciers (Barsch, 1996). However, evidence has been presented that rock glaciers could form from such deposits (Gorbunov, 1983; Vick, 1987; Brideau *et al.*, 2007) and catastrophic rockfalls are responsible for the morphological shape (Degenhardt, 2009).

Figure 7 around here

Large morainic rock glaciers situated below glaciers are typical for the study area. Hence, they might consist of mainly of glacier ice covered by moraines as e.g. suggested by Whalley and Martin (1992). However, the existence of thick glacier ice at altitudes below the permafrost belt would most likely lead into thermo-karst features as they are common for debris-covered glaciers (Nakawo *et al.* 2000) while these rock glaciers have ridges and furrows and a fresh steep front as being typical for creeping permafrost (Haeberli et al. 2006). Although being much larger, the morainic rock glaciers of the study area show strong similarities with the well investigated Gruben rock glaciers in the Swiss Alps (e.g. Haeberli, 1985; Kääb, *et al.* 1997, Kääb and Reichmut 2005). The upper part of the rock glacier is affected by historical fluctuations of the polythermal Gruben Glacier. This “glacier-affected” part contains dead ice from the glacier and shows thermo-karst features (Kääb *et al.,* 1997). These observations are in line with the conclusions based on surface observations by Gorbunov (1979) that glaciers advanced over the upper parts of the rock glaciers in periods of glacier advances during the Little Ice Age, resulting in depressions in their upper reaches (e.g. Figure 7). The “periglacial” part of Gruben rock glacier shows a predominantly surface subsidence but also some surface lifting and Kääb et al. (1997) conclude that “growth and degradation of permafrost can take place simultaneously at different places within the same rock glacier”. Accordingly, Gorodetzkij shows active and inactive parts within its tongue (Gorbunov and Titkov, 1989; Kokarev *et al.* 1997). The occurrence of glacierets and smaller polythermal glaciers seem to favour the development of rock glaciers through provision of meltwater from the temperate accumulation areas (Etzelmüller and Hagen, 2005; Heaberli, 2000). This situation seems also to be typical for the northern Tien Shan.

6. Conclusions

Rock glaciers are wide-spread phenomena in northern Tien Shan and especially moraine rock glaciers cover a relatively large area. Glaciers above these rock glaciers are relatively small and surrounded by permafrost. Our modelled permafrost distributions indicates that the rock glaciers originate in the zone where permafrost is very likely and some large rock glaciers flow down in likely permafrost-free area. Here, we have shown that the occurrence and characteristics of the rock glaciers can partly explained by the characteristics of their contribution area but the correlations are generally weak (r-values of ~0.3 to 0.4) and taken together the different topographic characteristics can only explain slightly more than 50% of the variance of the rock glacier area and their minimum elevation. The correlation is higher for the debris rock glaciers. No significant relation of the lithology and climatic variables (radiation, temperature, precipitation) to rock glacier size could be found, but a weak correlation of the mean temperature and radiation of the contribution area to the minimum elevation. Hence, there must be further reasons for the distribution and characteristics of the large rock glaciers in Tien Shan. We hypothesize that intensive weathering and rock avalanches triggered by seismic activities are important factors for the large dimensions of some rock glaciers and the variability within similar topographic and climatic settings. The meltwater from glaciers provides moisture input while the favourable thermal condition within these ’bouldery’ rock glaciers prevents their tongues from melting. However, detailed further investigations are needed to clarify the origin. These should concentrate on their movement (e.g. photogrammetric investigations, airborne LiDAR surface measurements and terrestrial laser measurements), on the surface deformation, and investigations of their internal structure based on geophysical soundings and drill boreholes.

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Tables

Table 1: Calculated parameters of the rock glaciers and their contributing areas.

Nr.	Parameter	Abbreviation
1	Area	a
2	Perimeter	pe
3	minimum elevation	h_{min}
4	maximum elevation	h_{max}
5	mean elevation	h_{mean}
6	elevation range	h_{range}
7	headwall height	h_{HW}
8	headwall area	a_{HW}
	mean slope	sl_{mean}
9	mean aspect	asp_{mean}
10	mean radiation input	rad_{mean}
11	mean annual air temperature	t_{mean}
12	mean annual precipitation	pr_{mean}

Table 2: Characteristics of the selected rock glaciers and its contributing areas based on Fest (2007), Gorbunov and Titkov (1989), and own investigations.

	Rock glacier							Contributing area					
Rock glacier	asp	a [km²]	h_{min} [m asl]	h_{max} [m asl]	h_{Front} [m]	l_{max} [km]	sl_{mean} [°]	a_{noice} [km²]	h_{maxCA} [m asl.]	h_{HW} [m]	sl_{maxCA} [°]	sl_{meanCA} [°]	$r_{RG/CM}$
Burkutty	NE	0.60	3040	3460	45	1.5	13.7	1.88	3940	475	48.3	26.9	0.32
Morrenij	N	1.19	3020	3376	50	1.2	11.6	1.40	4086	720	45.71	24.9	0.85
Nr. 127 (Ordzhonikidze)	NE	1.95	2725	3510	80	2.7	15.6	3.55	4360	850	56.3	24.6	0.55
Chon-Aksu	SE	1.62	2970	3790	80	3.2	15.0	7.15	4530	740	57.9	23.9	0.23
Karakorum	N	1.30	2650	3430	50	3.7	14.2	2.42	4200	770	48.1	23.1	0.61

Table 3: Statistics for the investigated 72 rock glaciers and its contributing areas in Northern Tien Shan.

Rock glacier variables						
	Area [km²]	Slope [°]	Altitude [m asl.]	MAAT [°C]	Precipitation [mm/a]	Pot. Radiation [W/m²]
Mean	0.36	15.7	3423	-3.55	1004.6	214.6
Std deviation	0.33	5.6	172.64	0.99	236.2	34.9
Minimum	0.02	9.6	2654	0.32	553.0	114.2
Maximum	1.95	39.2	3943	-7.32	1349.0	311.0

Contributing area variables								
	Area [km²]	Ice-free Area [km²]	Headwall height [m]	Slope [°]	Altitude [m asl.]	MAAT [°C]	Precipitation [mm/a]	Pot. Radiat. [W/m²]
Mean	4.19	2.64	633.2	25.3	3778.6	-7.8	1125.7	207.1
Std dev.	5.10	3.05	229.9	3.8	163.1	1.0	203.7	36.5
Minimum	0.12	0.12	224.9	18.5	3102.0	-1.4	681.4	42.6
Maximum	27.18	14.70	1200.3	60.3	4601.9	-10.9	1404.2	302.1

Table 4: Selected results of linear regression tests (n=72).

Test	r	p-value		R	p-value
a RG vs.			h_{min} RG vs.		
			a RG	-0.61	<0.000
a CA $_{ice\ free}$	0.34	0.004	a CA $_{ice\ free}$	-0.31	0.008
$R_{a/pe}$ CA $_{ice\ free}$	0.52	<0.000	$R_{a/pe}$ CA $_{ice\ free}$	-0.47	<0.000
h_{max} CA	0.33	0.004	h_{max} CA	-0.05	0.69
H_{range} CA	0.52	<0.000	H_{range} CA	0.65	<0.000
rad_{mean} CA	-0.11	0.360	rad_{mean} CA	0.49	<0.000
T_{mean} RG	0.33	0.005	T_{mean} CA	-0.46	<0.000
sl_{max} CA	0.34	0.004	sl_{max} CA	-0.47	<0.000
sl_{mean} RG	-0.26	0.029	sl_{mean} RG	0.05	0.430
$R_{a/sl}$ CA	0.27	0.024	$R_{a/sl}$ CA	-0.26	0.027
h_{HW}	0.28	0.031	h_{HW}	-0.45	<0.000
a_{HW}	0.30	0.042	a_{HW}	-0.21	0.061

r=correlation coefficient, p-value=Pearson's probability value, a=area, pe=perimeter, h=height, T=temperature, sl=slope, rad=radiation, R=ratio, RG=rock glacier, CA=contributing area, HW=headwall.

Figures

Figure 1: Map of the study area. The detailed study area is indicated by the black rectangle.

Figure 2: Morraine-derrived rock glaciers in Northern Tien Shan; A: Morrenij (Photo: S. Marchenko), B: Chon-Aksu (Kalgan Tash, T. Bolch), C: Nr. 127 (Ordzhonikidze, T. Bolch), D: Burkutty (M. Fest).

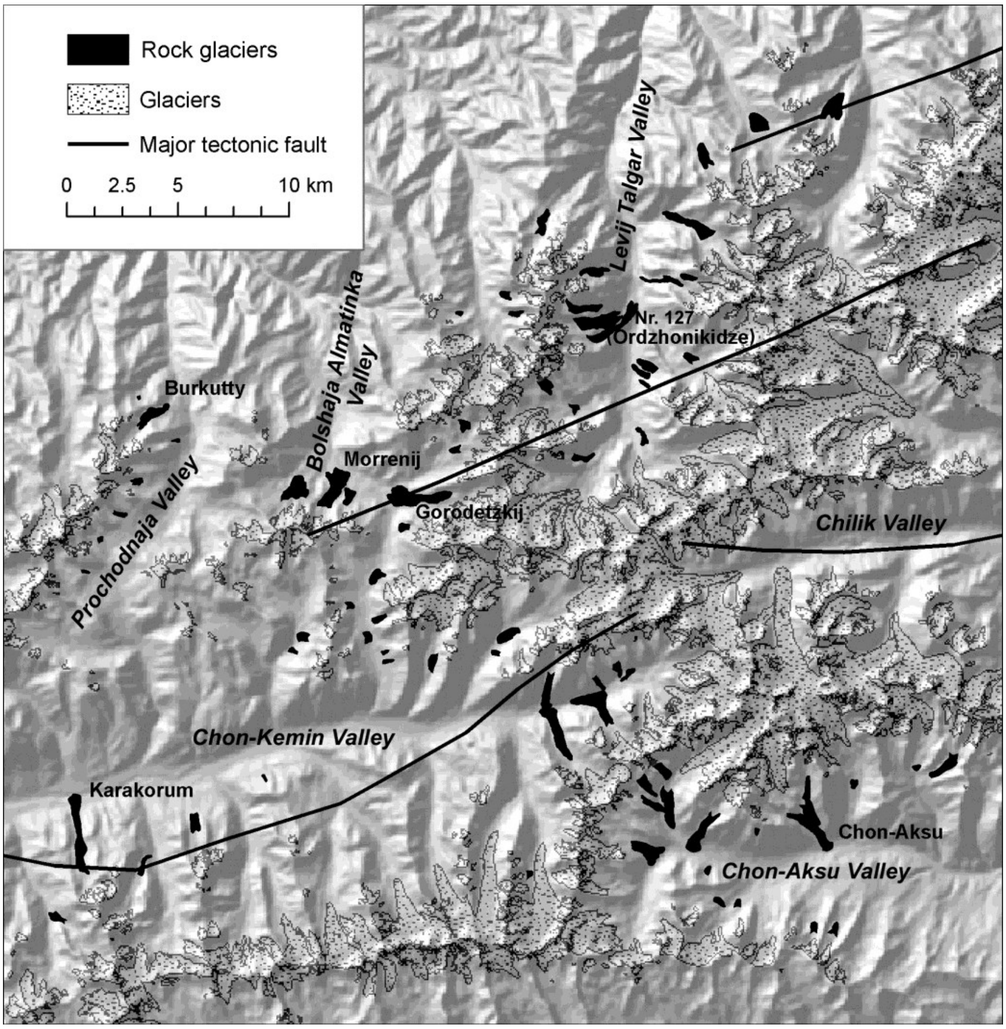

Figure 3: Map of the investigated rock glaciers. Glacier extents are based Landsat scene from 1999 (Bolch 2007). The tectonic faults are based on the Soviet Geological Map 1:500'000.

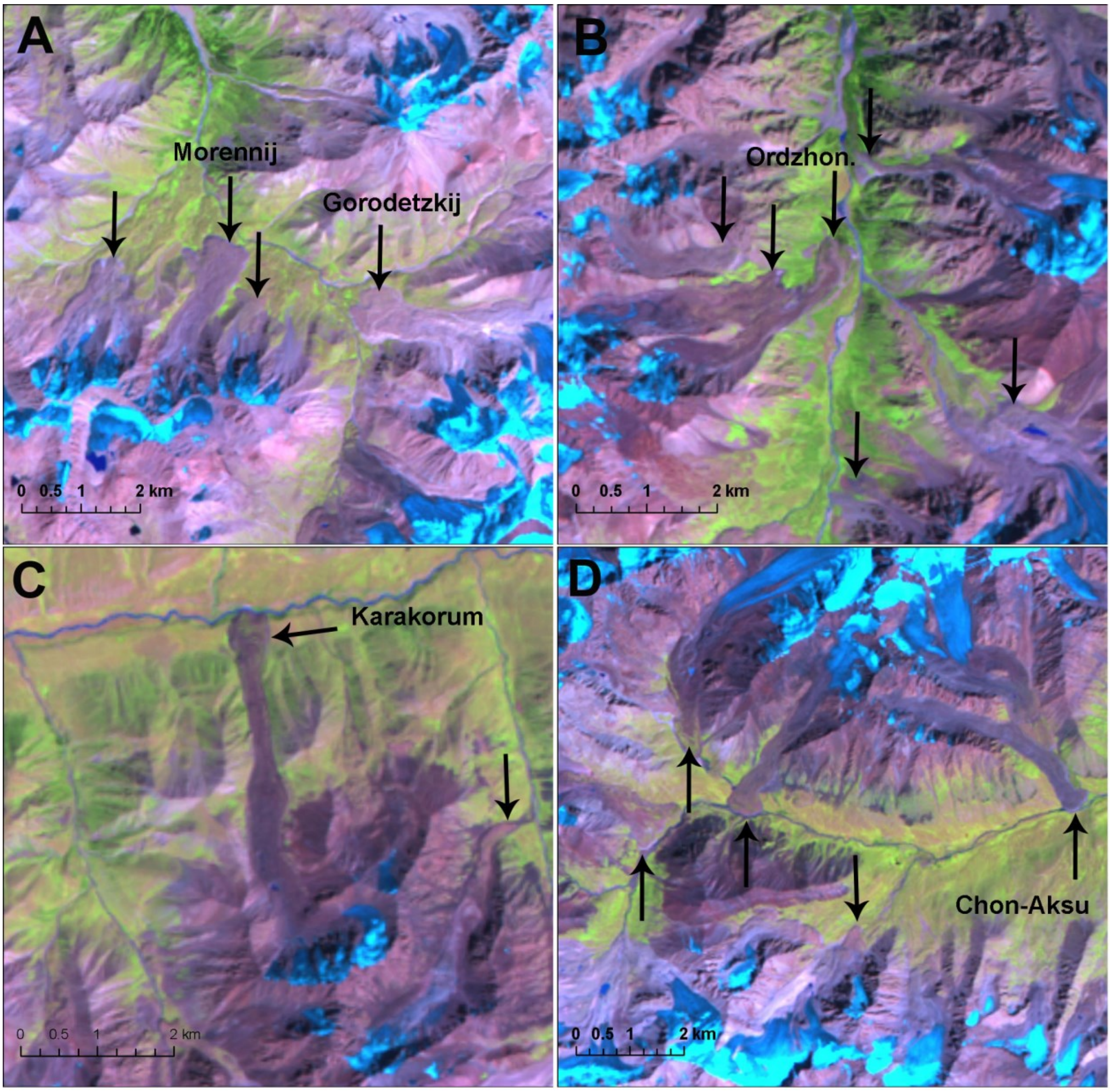

Figure 4: Selected valleys with characteristic rock glaciers (indicated by arrow, partly with names) showed on Landsat ETM+ or TM scenes (Bands 5-4-3, snow and glaciers appear blue); A: Ulken Almaty Valley (Morennij and Gorodetzkij), B: Levij Talgar Valley (Ordzhonikidze), C: Chon-Kemin Valley (Karakorum), D: Chon-Aksu Valley.

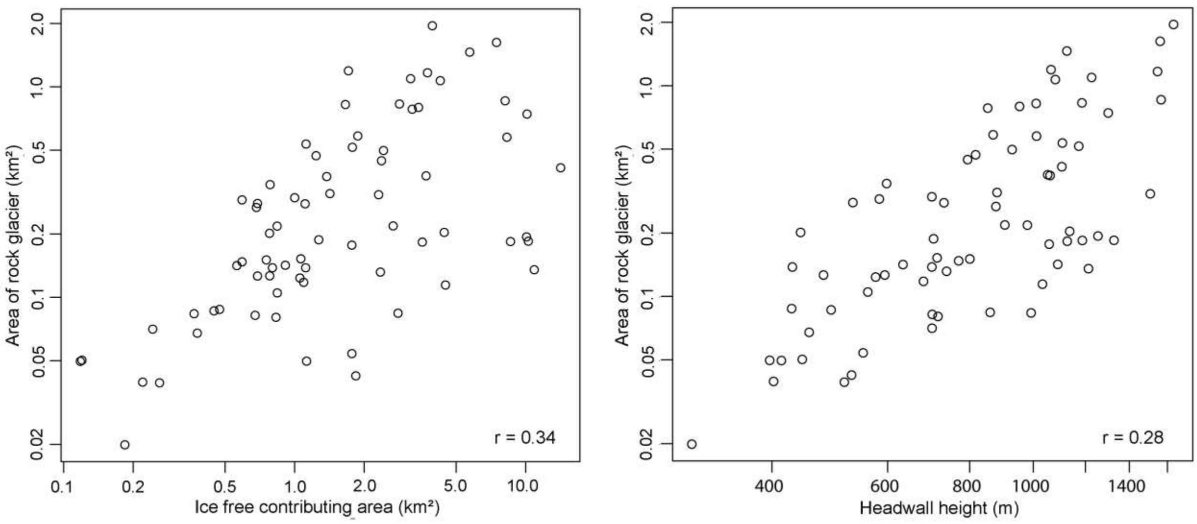

Figure 5: Relation between the rock glacier area and the ice free contribution area (left) and the headwall height (right).

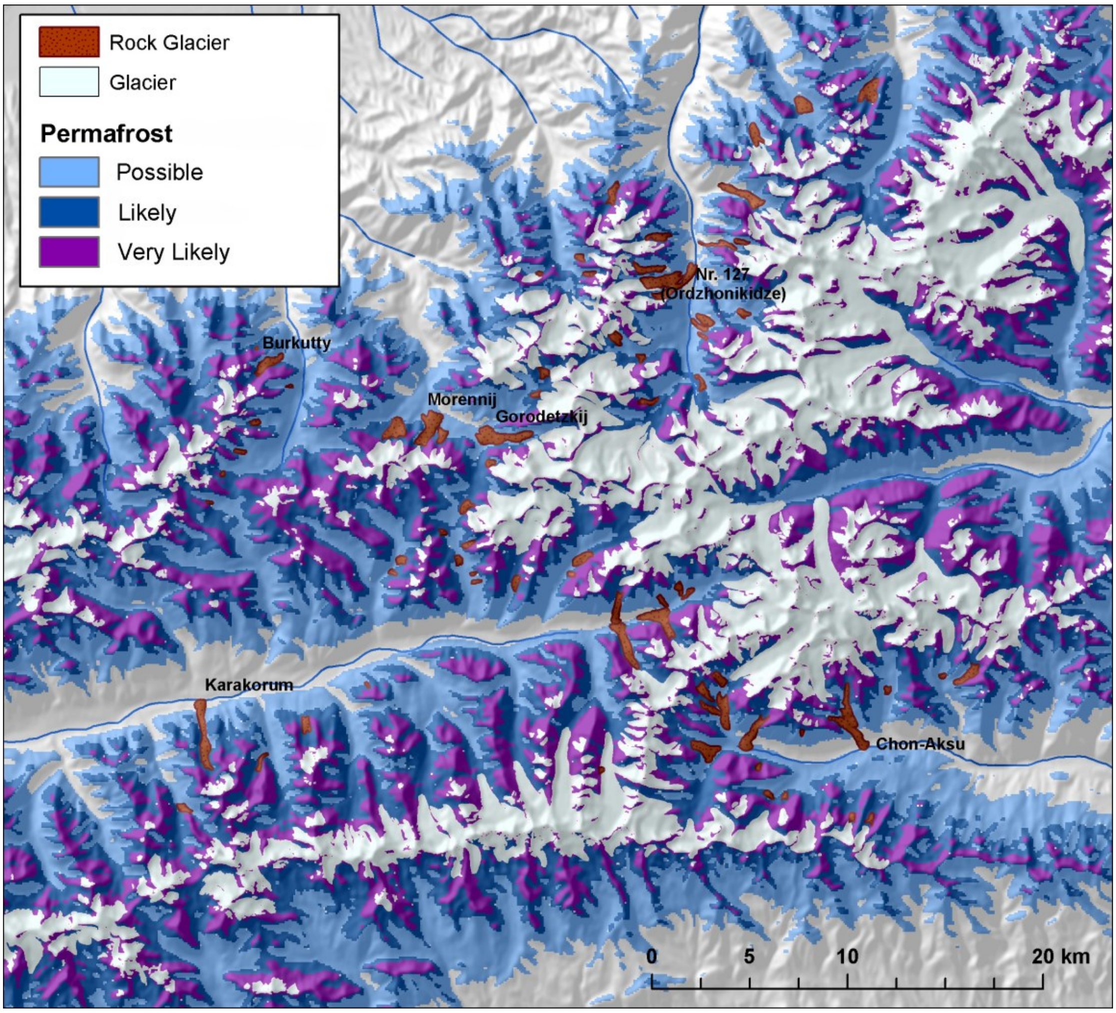

Figure 6: Map showing the modelled permafrost extent and the location of the rock glaciers.

Figure 7: Air photograph showing Gorodetzkij rock glacier. The depression with the pond below the glacier is the ’glacier-affected” part while the ‘periglacial’ part shows the typical ridges and furrows. Debris sources stem mainly from morainic material and the rockwalls.